802.15.4, a MAC layer solution for PLC

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Abstract

Technology evolution have made possible to connect all kind of devices to IP network. This becomes an evident objective for sensors networks research. The IETF 6LoWPAN RFC proposal was developed in that sense to use the benefit of IPV6 over wirelessly connected sensors (WSN). The IEEE 802.15.4 MAC layer stack being popular in the domain of wireless sensors within constrained resources, a few 6LoWPAN adaptations already exist. In this paper, we investigate the possibility of using IPv6 for sensor networks connected through powerline communication (PLC) non-wireless mediums and demonstrate possible interoperability. This document propose the first adaptation of the IEEE 802.15.4 commons standard on PLC medium. Following this standard interface, we demonstrate the possibility to carry out data on PLC with great reliability, and low power energy requirement using our WPC^{TM}physical layer (called Watt Pulse Communication (WPC)). This allows to benefit from the development of WSN research for PLC communication networks. Moreover, such a IEEE 802.15.4/6LoWPAN communication stack provides a generic communication standard for heterogeneous sensors networks. Thus, we finally demonstrate interoperability with tests between powerline and wireless sensor networks running IEEE 802.15.4/6LoWPAN stacks.

Keywords: Sensor networks, PLC, 802.15.4, 6LoWPAN, LR-WPAN, Adaptation layer, Interoperability.

1 Introduction

During the last few years, the world of sensor networks has considerably grown, and significant research has been made to enable the Internet of Things [1] becomes a reality. Major developements have been made, in particular in the field of wireless sensor networks (WSN) with the implementation of the IEEE 802.15.4 standard [2] as the main lower layers of the communication stack. The IETF 6LoWPAN RFC [3] enables the use of IPV6 over IEEE 802.15.4, and creates a convergence of sensor networks with IP world. This convergence is clearly demonstrated by the rapid growth of the IPSO (IP for Smart Object) alliance [4] in only one year, and the choice of the Zigbee alliance to support IP [5]. It is now obvious that IP will be the common language for smart devices and especially for sensor networks [6]. Most of the hard work done by 6LoWPAN for header compression for instance, would actually work quite well over other media. Moreover, great developments effort based on the IEEE 802.15.4 standard in the sensor networks field have been made in the wireless domain. However, like every media, wireless communications have some limitations. In particular, the radio range is depending on the environment, and some elements (such as grounded metal) make the radio transmission collapse. Persons moving in a house, opening or closing a door or starting a microwave oven affect the reception of weak radio signals. Reflections and absorptions may cause a reliable radio link become unreliable for a period of time and then being reusable again, creating lossy networks. Though, in a building or urban context, a reliable network is already installed and available : the power grid. [1]

The grid is a good way to carry data through an entire building or town without being affected by obstacles such as walls, floors or even the weather, because there is always a physical link between each point of the network. From this observation, it seems obvious to propose powerline communication (PLC) into sensor networks efforts. Many PLC communication protocols exist, but many manufacturers have developped their own. Unlike PLC devices which aim to provide a high data rate (up to 200 Mb/s for Homeplug AV standard [7]), the transceiver that we studied works in the low data rate domain (less than 250kb/s). This transceiver aims to keep the power consumption, size and cost as low as possible. The approach is actually rather similar to low rate wireless personal area network (LR-WPAN). Regarding these similarities, the large use of the IEEE 802.15.4 protocol in sensor networks and the perspectives, we explored ways to carry data over PLC using the IEEE 802.15.4 format. The paper is organized as follows : The section 2 is a short presentation of the PLC transceiver we used. The section 3 focuses on the main differences between RF and PLC from a MAC layer point of view and justify the need of an adaptation of the IEEE 802.15.4 standard over PLC. Section 4 explains the adaptation of this standard over PLC with the transceiver presented in the first section. The section 5 shows an interoperability experimentation of this adaptation between RF and PLC nodes. The section 6 presents the future work provided by such an implementation.

2 WPC™technology

2.1 WPC™principles

WPC ™[8] stands for "Watt Pulse Communication". It is a technology developed by Watteco [2], which enables to carry out any type of low data transfer communication with a reliable propagation and can be deployed on the same powerline network with other technologies without interfering. This transceiver is based on the transient behaviour of electrical networks. By using network reaction respect to load change, it is possible to create high level, low energy pulses (compliant with EMC regulation). As a result, the pulse magnitude can be significantly higher than noise even after propagation and ensure a robust communication signal. The coupling device is very simple and the network reacts with its own resonance ensuring a very good propagation medium. This technology takes advantage of a physical natural phenomenon: the ignition pulse produced by appliances connected on an electric network. A pulse is a very short (a few nanoseconds) pulse produced by a load during its ignition or extinction and constitutes an unambiguous signature. The WPC™module includes a microcontroller driving an adapted load, producing the pulse when connected to the mains. This pulse propagates over the power line at a long distance (up to 1 km in a public lighting environment). The emission of pulses can be triggered according to a controlled time schedule in order to communicate between two points of an electric network.

[1] Note : The word "Powerline" is used for "mains power" or "mains signalling"(UK) or "line power" or "power lines" (American). It means the domestic (or residential) power supply or AC Power.

[2] http://www.watteco.com

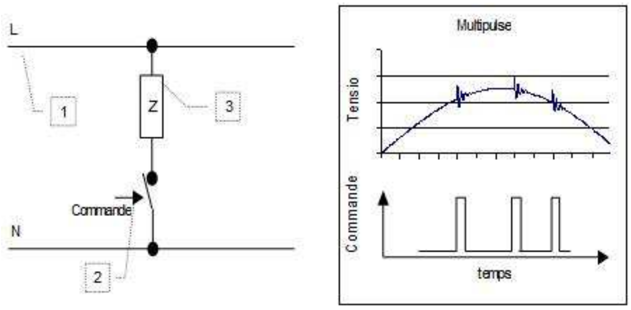

Figure 1: WPC^{TM}comunication principle

The chip has the following characteristics:

- A small size (approximately 500 mm2), induced by the network coupling method.
- A low power consumption (less than 10 mW), due to the coupling method and the simplicity of the reception floor.
- A reduced cost of electronics (i.e. dollars order for large quantities), induced by the communication with pulses. This allows simplicity for broadcasting data and front-end anological receiver, limiting electronic components and signal processing.

As a "powerline modem", it can be used for any type of data communication without any protocol restrictions. An OEM module can re-use any existing protocol providing a lower data rate than WPC^{TM}can generate. In this paper we focus on the IEEE 802.15.4 standard protocol.

Data rate	10kb/s bi-directional
Digital Connection	Direct RX/TX or SPI serial mode
Frame Check and Correction	8 bits CRC and Hamming encoding
Input Voltage	110 to 230V, 50-60Hz
Power Supply	5V DC
Power Consumption	10mW on average on communication

Figure 2: WPC Technical features

2.2 Applications

- SMART METERING : Smart Meters for Smart Grid applications (Smart Grid): optimization of energy consumption per household managed by the energy supplier (Demand Response). Optimization of peak consumption.
- HOME CONTROL : Control and automation of electrical habitat (home automation): Heating / Air / Ventilation, Lighting, Security, Home appliances, TV / Hi-Fi
- HOME AREA NETWORK : Network control and communication between electrical devices to achieve an effective energy management and habitat: monitoring the consumption / energy production (monitoring), management of habitat remotely smart meter (Smart Metering).
- STREET LIGHTING : Effective management of public lighting: individual control and away from streetlights, lampposts communicating, automation and brightness adjustment.

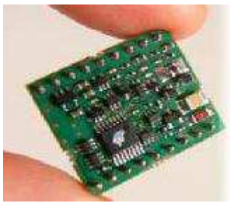

Figure 3: The WPC Transceiver from Watteco

3 MAC Layer Context

The IEEE 802.15.4 standard has been originally written for radio frequency (RF) devices, so it could be unusual to have a PLC device using this standard to communicate. To clarify this, a return to the standard rationale is needed: The goal of the IEEE 802.15.4 standard is to provide a common language through LR-WPAN. Unlike wireless local area networks (WLANs), WPANs involve little or no infrastructure. This feature allows small, power-efficient, inexpensive solutions to be implemented for a wide range of devices. A LR-WPAN is a simple, low-cost communication network allowing wireless connectivity applications with limited power and relaxed throughput requirements. The main objectives of an LR-WPAN are ease of installation, reliable data transfer, short-range operation, extremely low cost, and a reasonable battery life, while maintaining a simple and flexible protocol. IEEE 802.15.4 standard defines the protocol and compatible interconnections for data communication devices using low-data-rate, low-power, and low-complexity for short-range RF transmissions in a WPAN. The WPC^{TM}transceiver is a low data-rate, low power and low cost communication technology, and many LR-WPAN features previously described, fit really well with it. The main difference is the media employed, which could be used to communicate and either to power the node. WPC^{TM}nodes are therefore not constrained by the availability of energy because they have a reliable constant power source. This is the major difference with wireless nodes. But even if it is not restricted by the amout of power available, it is essential to keep the consumption of every node as low as possible for the smart home context. Using a few watts node consumption to control a few watts device is unwise. Powerline used as a media for communication provides a physical link between each node of the grid but the presence of a link does not mean that communication is always possible considering consumption, size, price and noise generated on the medium. The WPC^{TM}approach is to keep these factors as low as possible. As well as WPAN, communication between nodes is not always possible from any point of the grid. Like RF nodes, which can reach only their neigbours in a restricted area, WPC^{TM}nodes sometimes cannot reach some areas of the connected grid, depending on its topology and the loads connected. There is local dynamic signal strength that provide a sort of mobility feature on the electrical grid, depending on the electrical activity on the grid. The nodes being statics, this mobility might better be called reachability, regarding the position on the grid and the loads that can be pluged/unpluged on the grid at any time. The pluged/unpluged loads continually change the grid response and impact the communication possibilities on the medium. Therefore, WPC^{TM}is facing to the same problem of WSN concerning the possible unreliability of their medium. IEEE 802.15.4 dedicated to WPC^{TM}is a robust solution to low-rate communication over powerline. Associate to IEEE 802.15.4, it becomes an excellent way to provide an easy interoperability with LR-WPAN to merge the best of these two worlds and carry data on a heterogeneous low rate PAN with a better reliability.

4 IEEE 802.15.4 adaptation over PLC

The IEEE 802.15.4 standard defines the PHY and MAC layers of the OSI model. In this paragraph, we propose to adapt these two layers on WPC^{TM}. The original standard defines two different devices types that can participate in a network: a full-function device (FFD) and a reduced-function device (RFD). The FFD can operate in three modes serving as a PAN coordinator, a coordinator, or a device. A FFD can talk to RFDs or other FFDs, while a RFD can talk only to a FFD. A RFD is intended for applications that are extremely simple, such as a light switch or a passive infrared sensor. WPC^{TM}nodes used can operate as a FFD or a RFD, depending on the embedded software .

4.1 RF transceiver emulation over PLC

For the adaptation of the IEEE 802.15.4 standard over PLC, an open IEEE 802.15.4 RF stack is used. The goal of this adaptation is to emulate a RF transceiver with the WPC^{TM}transceiver. To achieve this, an enhanced SPI interface has been developped between the WPC^{TM}transceiver and the microcontroller to drive it as a "regular" RF transceiver.

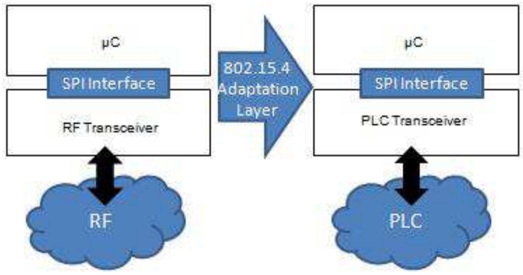

Figure 4: Emulation of a classic RF transceiver by a PLC transceiver trough an enhanced SPI interface

4.2 PHY adaptation

The PHY layer of the IEEE 802.15.4 standard provides the following services: activation/desactivation of the transceiver, Energy Detection (ED), Link Quality Indication (LQI), Channel Selection, Clear Channel Assessment (CCA), transmitting and receiving packets across the physical medium. The specific WPC^{TM}transceiver induces some timing adjustments because this transceiver transmits data only near the rising zero-crossing voltage while the reception is continuously possible.

The transceiver fragments every IEEE 802.15.4 frame in smaller packets. The actual data rate is about 10Kbits/s over 50Hz frequency, meaning that 25 bytes are sent every voltage period. Therefore the transceiver fragments data in 25 bytes packets sent near the zero crossing of the voltage. This specific communication introduces timing adaptations compared to a classic RF transceiver which has a continuous transmission. The PHY specifications of the IEEE 802.15.4 standard fully describes the physical interface (i.e. frequency band, modulation and data rate). For this specific transceiver, these specifications are reduced to minima. The attributes of the physical interface are written in the PHY PIB (PAN Information Base). This information base has been adapted to fit with our PLC transceiver.

- phyCurrentChannel : Unlike RF, there is only one channel available for our physical interface. The normalization for the different PLC frequency band is still in progress but a time slot in the 2-4 Mhz band has been already reserved for low rate PLC in the IEEE P1901 working Group [9]. This time slot is named "LRWBS" for Low Rate Wide Band Services and we use it to communicate.
- phyTransmitPower : This attribute is used to set the power of the transceiver transmission. The power transmission is constant for WPC^{TM}transceiver, so this parameter is set to a constant in accordance with PLC standards.
- phyCCAMode : This attribute specify 3 differents Clear Channel Assessment (CCA) modes, defined in the IEEE 802.15.4 standard. The CCA is performed with a specific method on WPC^{TM}transceiver.
- phyCheckCRC : This attribute is used to enable or disable the Cyclic Redundancy Check (CRC) checking. One CRC check is implemented in the WPC^{TM}transceiver so you can enable or disable this attribute.
- phyGenerateCRC : This attribute is used to enable or disable the Cyclic Redundancy Check (CRC) generate. One generation is implemented in the WPC^{TM}transceiver so you can enable or disable this attribute.

4.3 MAC adaptation

The MAC layer used over the WPC^{TM}transceiver is very close to the MAC layer defined by the standard. A few timing ajustments are needed regarding the specific communication. The MAC layer of the IEEE 802.15.4 standard provides the following services: beacon management, channel access, GTS management, frame validation, acknowledged frame delivery, association /disassociation, security. Timing attributes defined in the MAC PIB were increased to fit with WPC^{TM}physical interface.

- macAckWaitDuration : This attribute determines the time limit from non-received acknowledge. This attribute has been incremented in order to respect the transceiver specificity. This incrementation is a result of the modification of the MAC constant "aUnitBackoffPeriod" which takes part of the "macAckWaitDuration" attribute's calculation. This constant determines the number of symbols forming the basic time period used by the CSMA-CA algorithm, which is used in our adaptation layer.

4.4 Results of the adaptation

Regarding LR-WPAN features defined by the IEEE 802.15.4 standard, we can compare them with a WPC^{TM}network implementing our 802.15.4 standard adaptation.

	LR-WPAN	WPC^{TM}-PAN
Data rate	250, 100, 40, 20kb/s	10kb/s
Star or peer-to-peer	Ok	Ok
16-bit short or 64-bit extended addresses	Ok	Ok
Guaranteed time slots	Optional	not managed
CSMA-CA	Ok	Ok
Fully acknowledged	Ok	Ok
Low power	Ok	Ok (10mW)
Link quality indication	Ok	Ok
Channels	16 in 2450 MHz band 30 in 915 MHz band 3 in 868 MHz band	1 channel 2-4 MHz

Figure 5: LR-WPAN vs WPC-PAN

Our PLC adaptation clearly fits with the original definition of the IEEE 802.15.4 standard [2].

5 Experiment

In this section, an interoperability experiment between RF and PLC nodes using the IEEE 802.15.4 standard is shown. This is a first proof of concept of data transferts in a PLC/RF heterogeneous network. Such a MAC level experiment highlights a starting point of IEEE 802.15.4 interoperability. The future work will be fully IPv6 at the network layer with 6LoWPAN, which will be presented in the next section.

5.1 Hardware

5.1.1 WPC^{TM}Development Kit

The WPC^{TM}technology, was used through a "WPC Development Kit" from Watteco. It enables users to easily integrate a WPC^{TM}transceiver and to use it safely as an original commmunication tool on PLC.

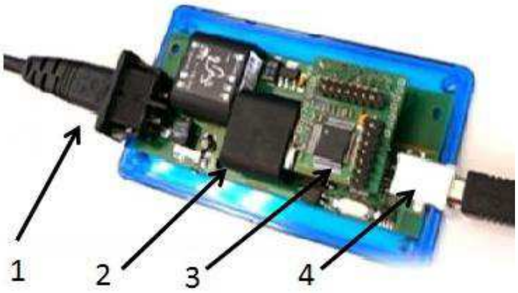

Figure 6: The WPC DevKit from Watteco

It is composed of 4 different parts :

1. AC Power
2. WPC^{TM}transceiver
3. Microcontroller
4. USB interface

The architecture is quite similar to a RF node which is basically composed of a microcontroller and a transceiver. Unlike RF nodes where the medium is the free space which does not need a connection, the WPC^{TM}transceiver needs to be connected to his medium through an electrical outlet. The USB interface provides a serial interface with the node. In this experiment, we used 2 PLC nodes with different configurations. The first one is a WPC^{TM}Development Kit connected to the PC gateway via its USB interface and connected to the grid, in order to send data over PLC. This device is used to relay the data sent from the gateway via the USB interface to the powerline medium. In a way, this device acts as a USB/PLC translator. The second one is a special form factor of the first node, with additionnal features. This device is called a "smartplug". It embeded a WPC^{TM}transceiver to communicate, control and command an electric relay to switch ON/OFF an electric device up to 16 amps, and an ADE chip to measure the electrical consumption of the device pluged into. A light bulb was plugged on this device to show the ON/OFF capability and create an electrical load to measure. This device acts as a light switch controlled by PLC, which is able to return some electrical consumption informations, the state of the switch, and an error message if the command fails.

5.1.2 WSN Node

Figure 7: Tmote SKY platform from Crossbow

This node is a classic RF node from Crossbow [3] composed of a TI MSP430 microcontroller (8Mhz microprocessor, 48k Flash, 10k RAM), a TI CC2420 RF transceiver (2.4GHz ISM-band carrier, 250kbps) IEEE 802.15.4 standard compliant, and an on-board antenna. It can be powered by USB, or with 2 AA bateries. This enable the node to be autonomous and mobile. The USB interface is used as a serial

[3] http://www.xbow.com

link and can also be used to power the node. This platform includes also some sensors to measure temperature, humidity, and light. In this experiment, 2 Tmote SKY are used. The first one acts as a sender. It reads its own light sensor value and sends it in a IEEE 802.15.4 frame via its antenna. This frame is broadcasted each second. This node is battery powered and can be placed anywhere. The second one acts as a listener to transmit the light sensor value received on its antenna to its USB interface. This node is connected to the gateway with an USB cable which powers it. This node act as a RF/USB gateway.

5.1.3 Gateway

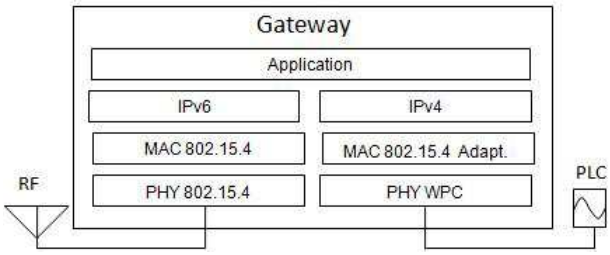

Figure 8: Gateway

The gateway builds an IEEE 802.15.4 bridge between Tmote SKY nodes and WPC^{TM}nodes. As this experiment is a first proof of the concept, the gateway runs here on a traditional PC computer. This gateway reads the data sent by the Tmote SKY via the USB interface, compares it to a threshold and send a command to the WPC^{TM}module via another USB interface. The threshold is set to define a darkness or brightness state from the light value collected. The state defined is then converted into a command to carry over PLC, that will finally switch ON/OFF the light bulb. In summary, we built an elementary light switch actuator, controlled by a RF sensor node, and running over IEEE 802.15.4 standard protocol.

5.2 Software

The 2 Tmote SKY nodes are running under the Contiki 2.3 OS [10]. This contiki version includes an IPv6 stack with an implementation of 6LoWPAN which brings the nodes the capability of exchanging IPv6 packets over IEEE 802.15.4 standard. Thus, the light sensor value transmitted between the 2 Tmote SKY nodes is carried in IPV6 packets. The 2 WPC^{TM}nodes are running under contiki 2.2 and the data transmitted between these nodes are carried in IPV4 packets. The first WPC^{TM}node transmit the command received from the gateway into UDP format. The smartplug decodes the frame and perform an ON/OFF action on the bulb. This node then returns the electrical consumption of the load connected with an UDP frame. It is then decoded by the first WPC^{TM}node which transmits this information to the gateway and plots the corresponding electrical consumption and the light value.

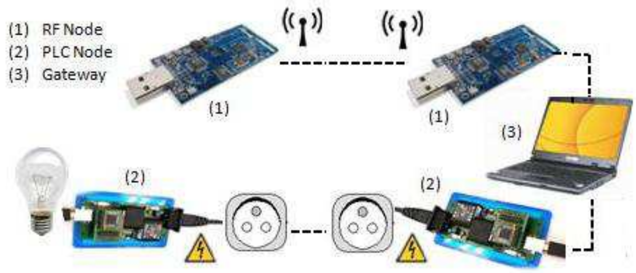

Figure 9: Schema of the experiment

The gateway bridges WPC^{TM}and Tmote SKY nodes at the application level. The software used in this experiment shows the data transmitted and provides a user interface to run the experiment.

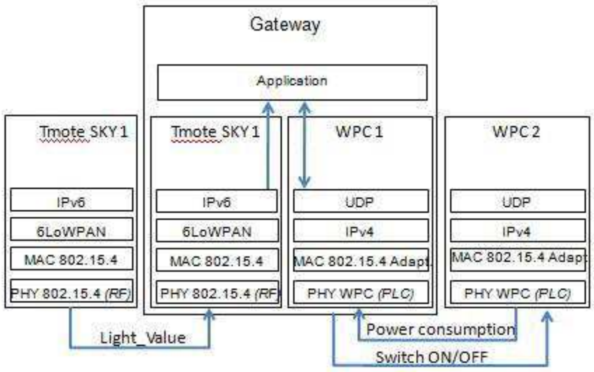

Figure 10: Communication layers

5.3 Results

Figure 9 shows the gateway interfaces, and the main characteristics of the experiment.

Figure 11: Two different light sensor values and the resulting switch state

Figure 11 describes the light sensor value recovered by the second Tmote SKY and received by the gateway.

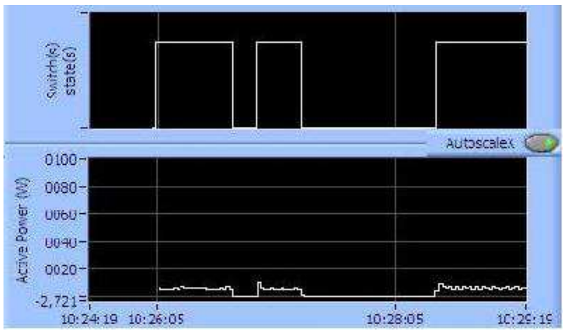

Figure 12: Histogram of the switch state and the corresponding power consumption

The first value read is 108 which is above the switch off value threshold (i.e. set to 80), so the bulb switch command is OFF. The gateway transmits the command to swith off the bulb and the switch state is set to OFF. When we hand seal the light sensor on the first Tmote SKY, the light value fall to 69, which is under the switch threshold value (i.e set to 70). The gateway transmits a switch-ON command to the smartplug and the switch state comes up. On the figure 12, an historic of the switch states is shown. The corresponding power consumption grows to 7 Watts when the light bulb is on : ON (upper value on the graph) or OFF (lower value on the graph). The power consumption follows nicely the switch state changes, with a little variation of the consumption when the bulb is on. This little variation is due to the low power fluocompact bulb used and the lack of precision relative in the very low range of the power measurement of the ADE chip (which can measure a consumption up to 3000 Watts). The different frames exchanged during these actions are represented below :

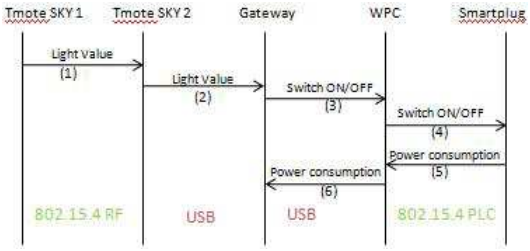

Figure 13: IEEE 802.15.4 frames exchange diagramm

6 Future Work

6.1 Interoperability

From this work, it is now possible to provide a simple standard communication over WPC^{TM}to open the PLC communication layer to others media. A group of the IPSO alliance [4] is currently working on the defintion of a minimal set of primitives to provide a basic data exchange between IEEE 802.15.4 nodes. The goal of this group is to make various nodes communicate with a minimal subset of IEEE 802.15.4 primitives and perform interoperability tests between different platforms. Interoperability tests are planed for 2010. Including our PLC into these tests is an important outlook for interoperability in sensor networks. Each media has its own strength and weakness, therefore it will be important to provide a multi-medium data exchange capability that enables top layers to take advantage of each media when necessary.

6.2 Gateway

The gateway used in this experiment will be subject to numerous changes and exploitations, taking into account ongoing constraints. An extensive study is already underway to decide at which level of the communication stack the bridge has to be built. Such a gateway should be as simple as possible with minimal ressources, size and cost to be realistic from the indutrial standpoint.

6.3 6LoWPAN

Another great development for our PLC implementation is to quickly switch from IPv4 to IPv6 which is the logical IP support for sensor networks. Using IPV6 over IEEE 802.15.4 requires some adaptations defined by 6LoWPAN in RFC 4944 [3]. This feature which is under study for WPC^{TM}is offered in some OS like Contiki or TinyOS [11].

6.4 Routing Over Low Power and Lossy Networks (ROLL)

A big development effort is currently performed at IETF to provide routing capability in low power and lossy networks (LLN). This working group is ROLL. The RPL protocol [12] will be available early 2010. This protocol is agnostic of the media used. It will enable data exchanges in heterogeneous networks and that is exactly our view of the near future sensor networks. Morevover, this mesh-based and hops protocol will make our communication more reliable.

6.5 Beacon Enable mode

The beacon enable mode is a powerful mode defined in the IEEE 802.15.4 standard which assigns temporal slots to each device and avoid efficiently packets collision. However, this mode is very tricky to implement because it needs a global time synchronisation of the whole network. It is even more difficult to use it in an unstable network, and the use of such a mode can create a significant overload of traffic control. That is why we do not plan to support it.

7 Conclusion

The IEEE 802.15.4 standard implements many primitives which provide a very complete service in highly constrained network such as LR-WPAN. In this paper, we explored the similarities between LR-WPAN and WPC^{TM}-PAN and showed a simple adaptation layer of the IEEE 802.15.4 standard over PLC to extend the scope of LR-WPAN. With our adaptation, a large part of the IEEE 802.15.4 stack is implemented over PLC, with the use of the WPC^{TM}transceiver. The MAC/PHY primitives implemented with this adaptation provide a comprehensive IEEE 802.15.4 service over PLC which extends this medium to the IP world with the use of 6LoWPAN. It is a first implementation of a low power IEEE 802.15.4 network over PLC, which is extended to IP applications.

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